Potential Environmental and Human Health Impacts of Lithium-ion Batteries in Electronic Waste

Supporting Information

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Table A. Batteries Selected for Analysis

Analysis ID	Sample ID	Battery Chemistry	ITEM ID	DESCRIPTION	# in Recellular Inventory	Width (mm)	Length (mm)	Height (mm)	Weight (g)	Pre-Grind SMP+Bag (g)	Post-Grind SMP+Bag (g)
Li-Ion-1	BL03-1	Li-Ion	BLABBAT03087003-UOEM	PHONE 7250	10,750	38	50	7	26.05	30.18	22.83
Li-Ion-2	BL03-2	Li-Ion	BLABBAT03087003-UOEM	PHONE 7250	10,750	38	50	7	26.11	30.23	25.07
Li-Ion-3	NOB3-1	Li-Ion	NOKBBLB3-UOEM	PHONE 6340-6360-6370-6385	9,250	33	53	9	27.48	31.56	27.86
Li-Ion-4	AU00-1	Li-Ion	AUDBBTR9100-UOEM	PHONE 9100	8,250	31	56	7	23.48	27.62	23.33
Li-Ion-5	SAMBA-1	Li-Ion	SAMBAB553446BA-UOEM	PHONE T119-M240-M320-D407-D347-A837	8,000	34	49	5	20.2	24.28	20.34
Li-Ion-6	MOBK70-1	Li-Ion	MOTBBK70-UOEM	PHONE V950-I335-IC402-IC502	7,250	37	45	6	22.79	26.87	22

Li-Ion-7	KY81-1	Li-Ion	KYOBTXBAT081-UOEM	PHONE 2035	4,250	36	60	7	28.31	32.5	27.94
Li-Ion-8	SAN23-1	Li-Ion	SANBSCP23LBPS-UOEM	PHONE KATANA	3,750	38	45	5	19.37	23.49	20
Li-Poly-1	LGFM-1	Li-Poly	LGBLGLPAHFM-UOEM	PHONE RUMOR	5,000	46	69	5	23.68	27.51	25.82
Li-Poly-2	LGFM-2	Li-Poly	LGBLGLPAHFM-UOEM	PHONE RUMOR	5,000	46	69	5	23.91	28.1	26.03
Li-Poly-3	LGQM-1	Li-Poly	LGBLGLPAGQM-UOEM	PHONE VX8600	3,500	48	50	6	20.44	24.6	23
Li-Poly-4	ER37-1	Li-Poly	ERIBBST37-UOEM	PHONE Z300-Z520-Z525	3,250	35	48	5	19.39	23.53	21.09
*Smart-1	Ap01-1	Li-Poly	APPLE-08-003-01(GG)	PHONE iPhone 3GS	N.A.	41	68	4	23.14	27.27	22.42
*Smart-2	RIM-09-1	Li-Ion	RIMBAT-06860-009	PHONE Blackberry Curve 8530	N.A.	34	55	5	22.89	27.03	21.78
*Smart-3	MDBP6X-1	Li-Poly	MOTBP6X	PHONE Motorola Droid	N.A.	50	45	6	27.24	31.51	26.32
*Smart-4	MDBP6X-2	Li-Poly	MOTBP6X	PHONE Motorola Droid	N.A.	50	45	6	27.42	31.63	26.38

Footnote to TABLE A.

*Advances in cell phone technology include the rapid adoption of "smartphones," defined as phones with advanced capabilities, often with computer-like functionality. As smartphones advance, they also use more energy and necessitate the development of batteries that can meet their energy demands. The energy densities of Smartphone batteries are approximately 30% higher than batteries associated with older phones (average 0.58 MJ/kg). In the U.S., smartphone owners rose from 2% in November 2005 to 16% in November 2009 (comScore, 2010). 2.7 million people in the U.S. owned smartphones in an average month during the November 2009 to January 2010 period, up 18% from the August 2009 through October 2009 period (comScore, 2010). Moreover, in November 2009, 30% of mobile users said that they intend to purchase a new phone during the next three months and 69% of those said they plan to purchase a smartphone (comScore, 2010). Additionally in 2011, nearly 42% of cell phone subscribers used smartphones (comScore, 2012). Consequently, smartphones, and their batteries may become an increasing problem in the electronic waste stream if the infrastructure for collection and recycling are not developed appropriately.

References

comScore. 2010. Using Consumer Insights to Uncover Opportunities in Next Generation Mobile Devices. Presentation by Mark Donovan, SVP Mobile + Sr. Analyst, comScore, presented in Las Vegas, CES 2010, January 9, 2010. comScore Reports January 2010 U.S. Mobile Subscriber Market Share. Reston, VA March 10, 2010.

comScore. 2012. 2012 Mobile Year in Focus. February 2012.

Table B. Major components and chemical constituents of lithium batteries

BATTERY COMPONENT	TYPICAL CHEMICAL CONSTITUENTS
Negative Electrode (Anode)	CARBON GRAPHITE SILICON GERMANIUM LITHIUM TITANATE ($Li_4Ti_5O_{12}$)
Positive Electrode (Cathode)	LITHIUM COBALT DIOXIDE LITHIUM IRON PHOSPHATE LITHIUM MANGANES OXIDE NICKEL COBALT ALUMINATE NICKEL MANGANES COBALTITE
Electrolyte	ETHYLENE CARBONATE ETHYL METHYL CARBONATE DIETHYL CARBONATE or DIMETHYL CARBONATE PROPYLENE CARBONATE LITHIUM HEXAFLUOROPHOSPHATE
Separator	POLYETHYLENE or POLYPROPYLENE
Current Collectors	COPPER ALUMINUM
Cell Enclosures (Cases and Pouches)	NICKEL-COATED STEEL OR ALUMINUM POLYMER (PLASTIC)-COATED ALUMINUM FOIL
Charge Interrupt Devices	MECHANICAL PARTS
Positive Temperature Coefficient Switches	POLYMER
Battery Pack Protection Electronics	PRINTED CIRCUIT BOARDS, TYPICAL OF A COMPUTER
Battery Pack Enclosures	HARD PLASTIC OR METAL

TABLE C. Methods Used to Assess Resource Depletion and Toxicity Potentials					
	Assessment Method				
Impact Category	**Scheme**		**Characteristics for Weighting Factor**	**Unit**	**Developer**
Resource Depletion Potential	Life-cycle Impact-based	CML 2001	Ratio between Quantity of Resource Extracted and Reserve	kg antimony-eq[a]	University of Leiden, Netherlands
		EPS 2000	Resource Price from Market Scenario	Environmental Load Unit (ELU)	Chalmers University of Technology
Toxicity Potential	Hazard-based	Threshold Limit Value TLV)- Time Weighted Average (TWA)	Relative Hazard for Occupational Exposure Limit: Inverse of the Limit	m^3	American Conference of Governmental Industrial Hygienists (ACGIH)
		Permissible Exposure Limit (PEL)-TWA	Relative Hazard for Occupational Exposure Limit: Inverse of the Limit	m^3	U.S. Occupational Safety and Health Administration (OSHA)
		Reference Exposure Limit (REL)-TWA	Relative Hazard for Occupational Exposure Limit: Inverse of the Limit	m^3	U.S. National Institute for Occupational Safety and Health (NIOSH)
		Toxic Potential Indicator (TPI)	-R-phrase (Hazardous Substance Declaration) -Water Hazard Class -Maximum Admissible Concentration (MAK), EU carcinogenicity, Technical Guidance	TPI	Fraunhofer IZM, Germany

			Concentration (TRC)		
	Life-cycle Impact-based	CML 2001	USES 2.0 Model Describing Fate, Exposure, and Effects of Toxic Substances	Kg 1,4-dichloro-benzene-eq	University of Leiden, Netherlands
		TRACI 2.0 (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts)	Toxicological Properties such as Fate, Exposure, and Effect for Cancer, Non-cancer, and Ecotoxicity Potentials	- CTU_h (comparative toxicity units, human toxicity) - CTU_e (comparative toxicity units, ecotoxicity)	U.S. Environmental Protection Agency (EPA)

[a] "eq": equivalent

Table D. Metal Content in Percentage of Total Cumulative Weight of All Metals Analyzed, for the Average Within Each Battery Type as well as an Average Across All Three Types

Element	Li-Ion	Li-Poly	Smart	Avg of All	Std. Deviation
Aluminum	46.39%	20.74%	17.61%	28.24%	15.79%
Antimony	0.01%	0.01%	ND	0.01%	0.00%
Arsenic	ND	ND	ND	ND	
Barium	0.27%	0.02%	0.25%	0.18%	0.14%
Beryllium	ND	ND	ND	ND	
Cadmium	ND	ND	ND	ND	
Chromium	0.01%	0.00%	0.00%	0.01%	0.00%
Cobalt	24.67%	45.21%	53.36%	41.08%	14.78%
Copper	21.00%	26.02%	19.64%	22.22%	3.36%
Iron	0.95%	0.22%	0.08%	0.42%	0.47%
Lead	0.05%	ND	0.00%	0.03%	0.03%
Lithium	3.66%	6.34%	7.34%	5.78%	1.90%
Manganese	0.37%	0.16%	0.05%	0.20%	0.16%
Mercury	ND	ND	ND	ND	
Molybdenum	ND	ND	0.01%	0.01%	
Nickel	2.55%	1.19%	1.53%	1.76%	0.71%
Selenium	ND	ND	ND	ND	
Silver	0.01%	0.00%	0.01%	0.01%	0.00%
Thallium	0.04%	0.07%	0.09%	0.07%	0.03%
Vanadium	0.01%	0.00%	0.00%	0.00%	0.00%
Zinc	0.03%	0.02%	0.02%	0.02%	0.01%

ND=Not detected in battery type

Figure S1

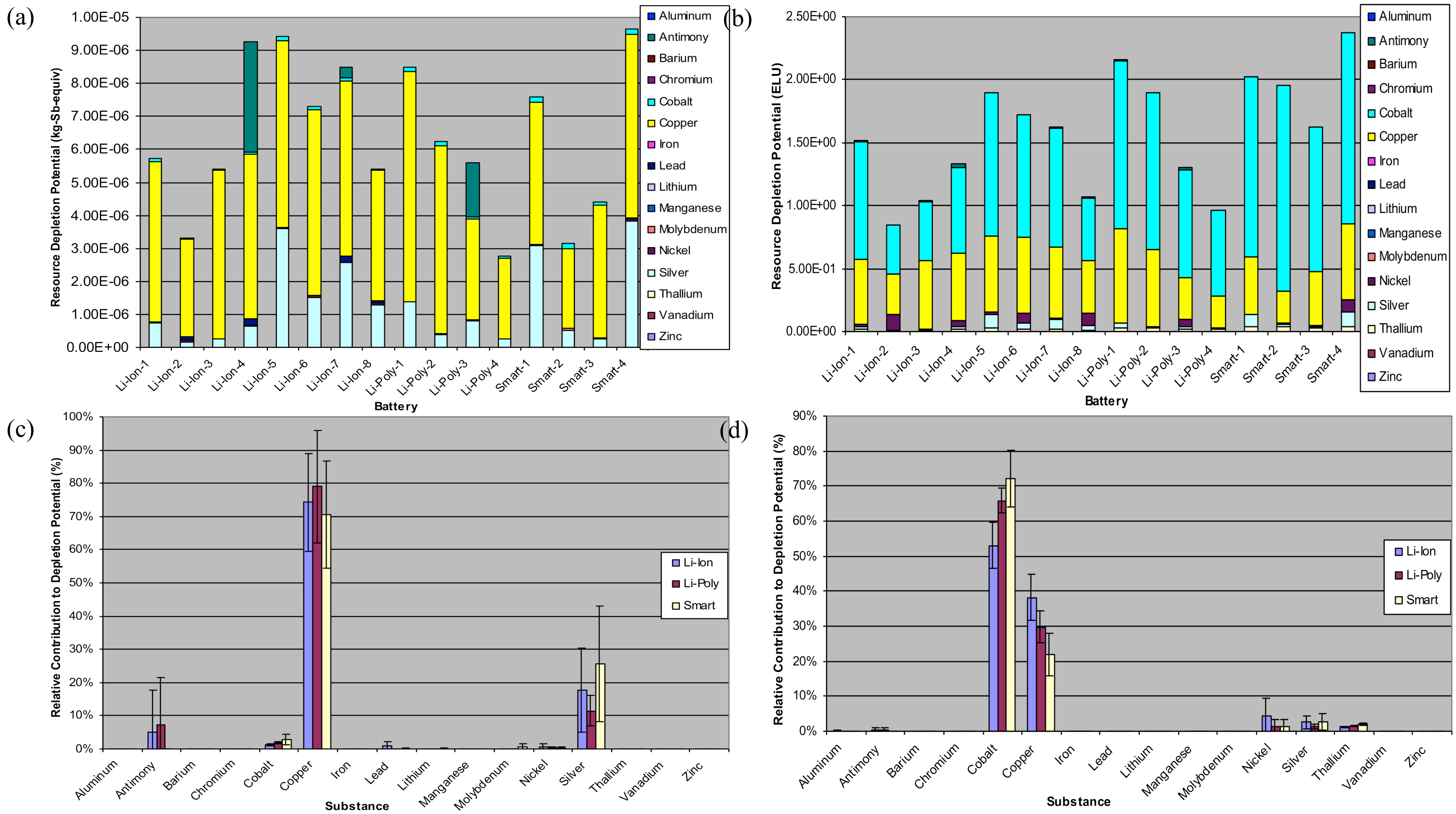

(a)
Resource Depletion Potential (kg-Sb-equiv)
1.00E-05
9.00E-06
8.00E-06
7.00E-06
6.00E-06
5.00E-06
4.00E-06
3.00E-06
2.00E-06
1.00E-06
0.00E+00
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Battery
Aluminum
Antimony
Barium
Chromium
Cobalt
Copper
Iron
Lead
Lithium
Manganese
Molybdenum
Nickel
Silver
Thallium
Vanadium
Zinc
(b)
Resource Depletion Potential (ELU)
2.50E+00
2.00E+00
1.50E+00
1.00E+00
5.00E-01
0.00E+00
Battery
(c)
Relative Contribution to Depletion Potential (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Li-Ion
Li-Poly
Smart
Substance
(d)
Relative Contribution to Depletion Potential (%)
Substance

Figure S2

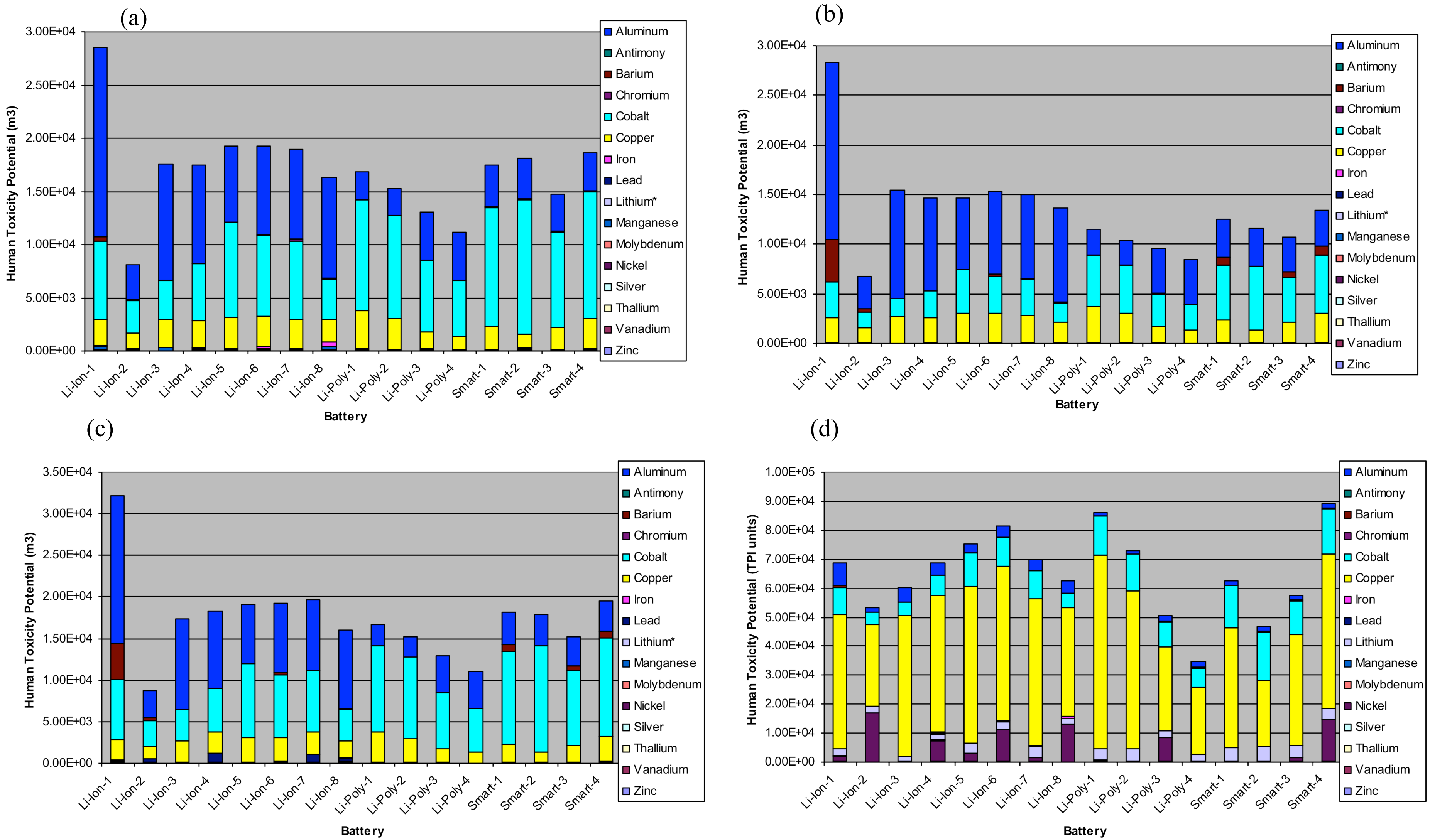

(a)
(b)
(c)
(d)
Human Toxicity Potential (m3)
Human Toxicity Potential (TPI units)
Battery
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Aluminum
Antimony
Barium
Chromium
Cobalt
Copper
Iron
Lead
Lithium*
Lithium
Manganese
Molybdenum
Nickel
Silver
Thallium
Vanadium
Zinc
0.00E+00
5.00E+03
1.00E+04
1.50E+04
2.00E+04
2.50E+04
3.00E+04
3.50E+04
1.00E+05

Figure S3

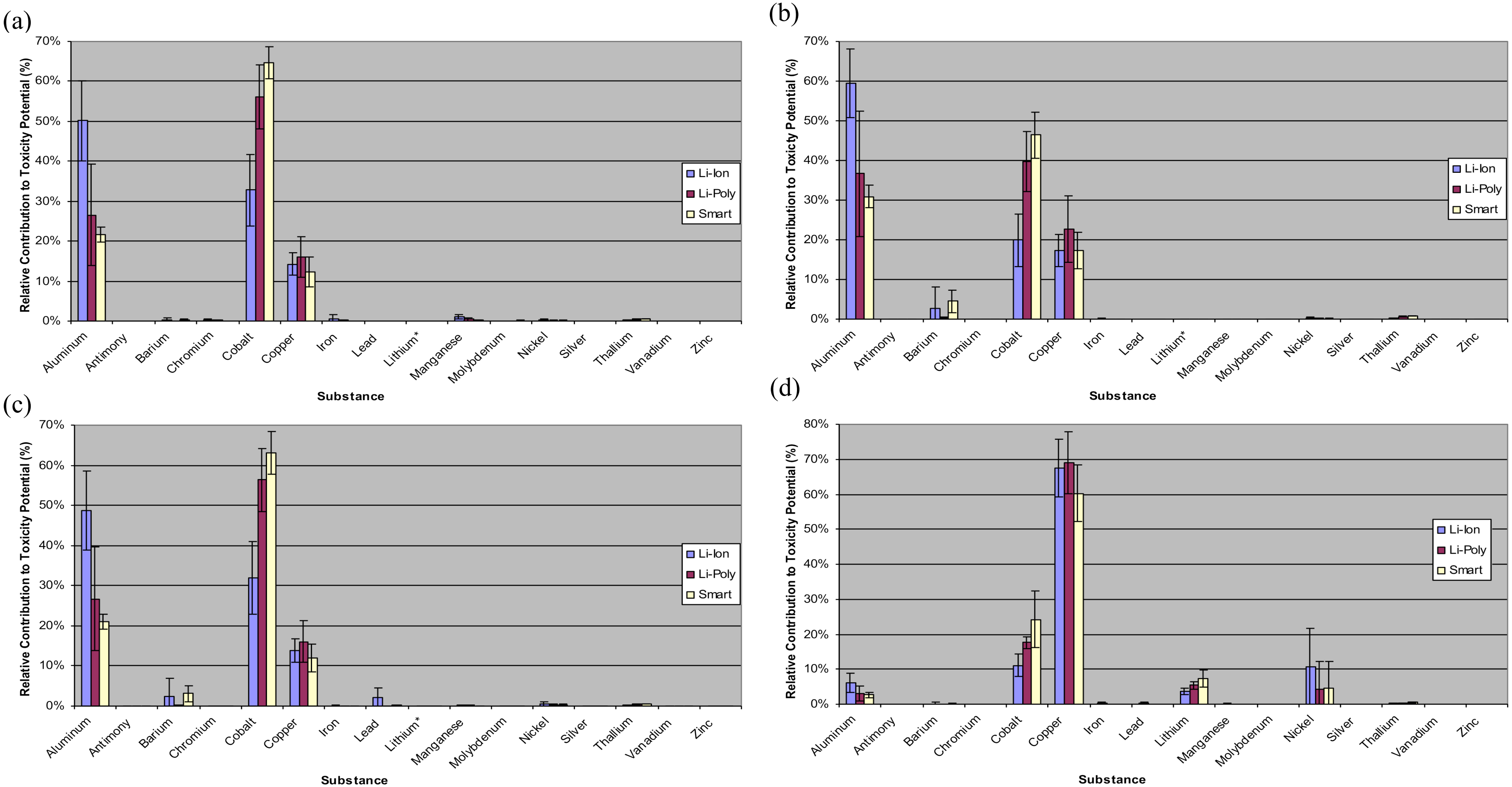

(a)
(b)
(c)
(d)
Relative Contribution to Toxicity Potential (%)
Substance
Li-Ion
Li-Poly
Smart
Aluminum
Antimony
Barium
Chromium
Cobalt
Copper
Iron
Lead
Lithium*
Lithium
Manganese
Molybdenum
Nickel
Silver
Thallium
Vanadium
Zinc

Figure S4

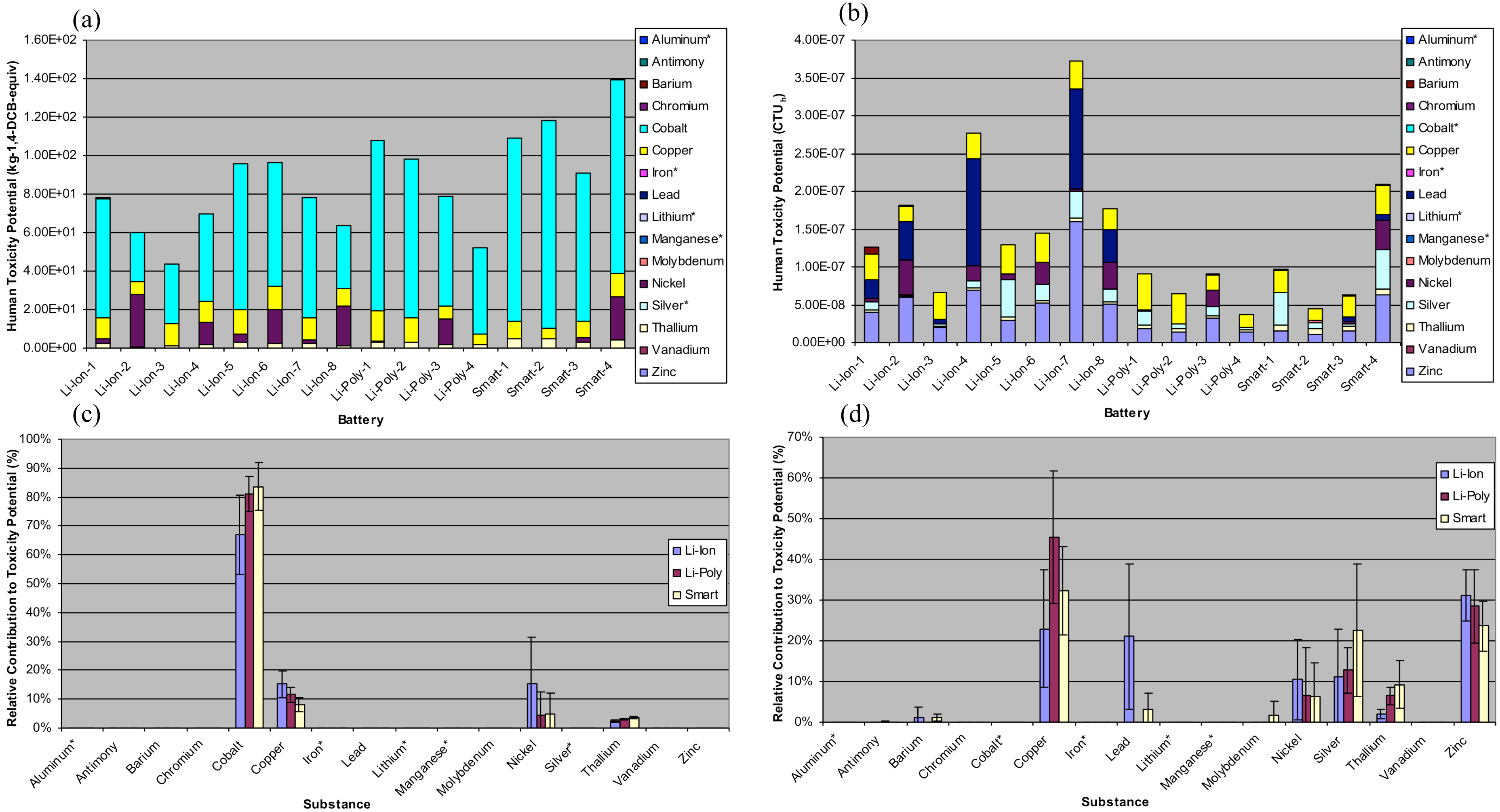
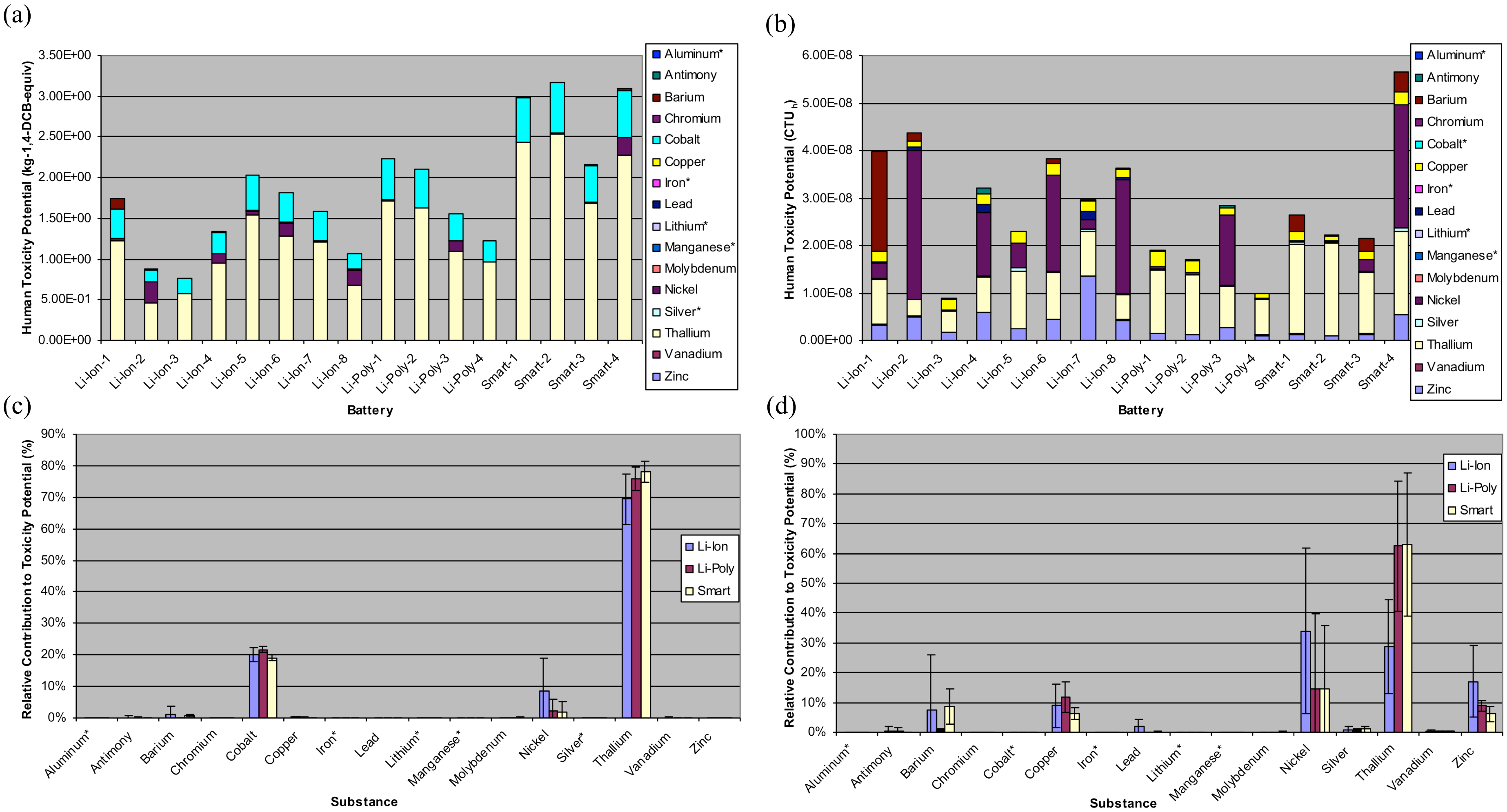
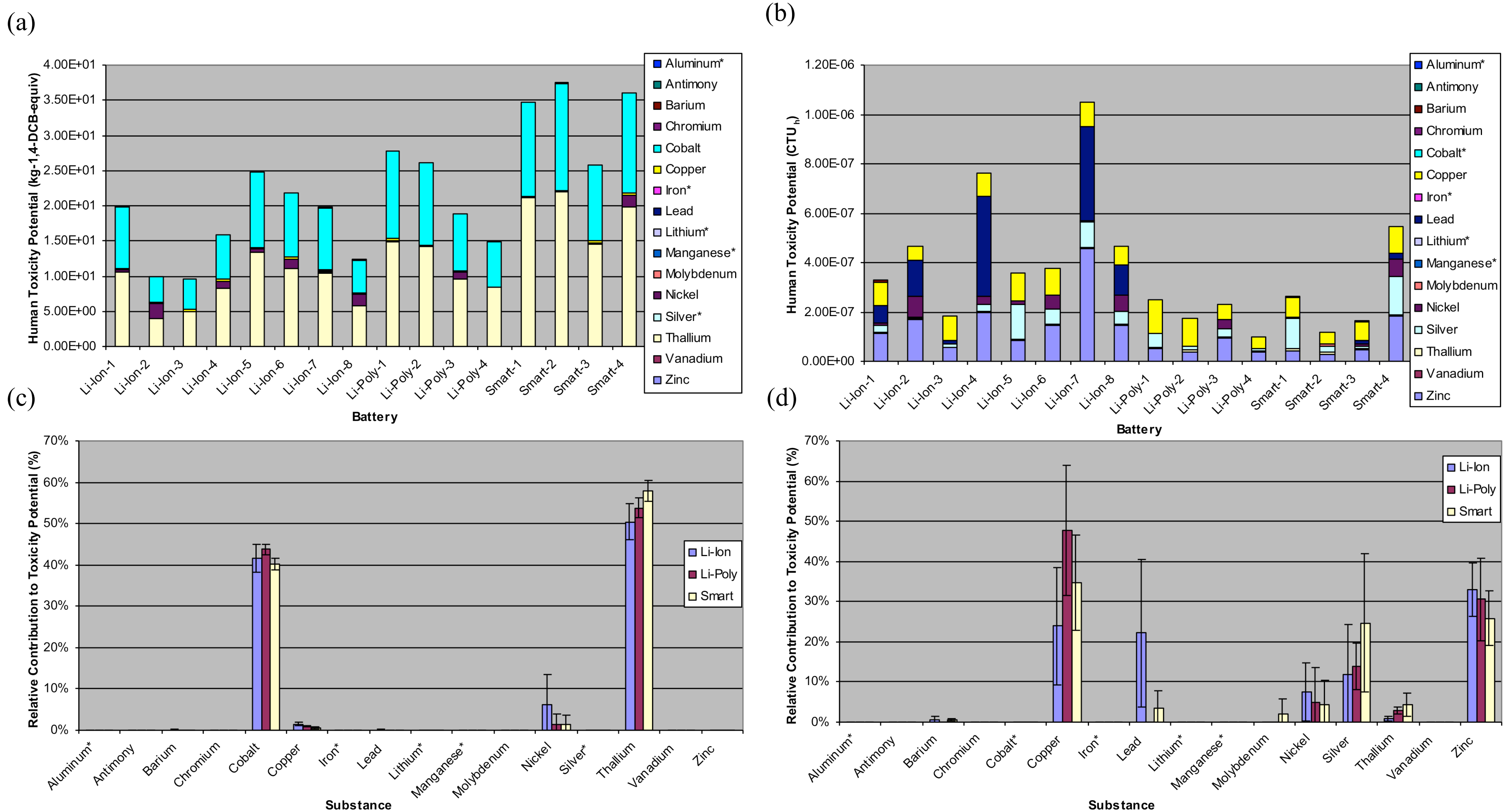

(a)
Human Toxicity Potential (kg-1,4-DCB-equiv)
Battery
Li-Ion-1 Li-Ion-2 Li-Ion-3 Li-Ion-4 Li-Ion-5 Li-Ion-6 Li-Ion-7 Li-Ion-8 Li-Poly-1 Li-Poly-2 Li-Poly-3 Li-Poly-4 Smart-1 Smart-2 Smart-3 Smart-4
Aluminum* Antimony Barium Chromium Cobalt Copper Iron* Lead Lithium* Manganese* Molybdenum Nickel Silver* Thallium Vanadium Zinc
(b)
Human Toxicity Potential (CTU_h)
Battery
Aluminum* Antimony Barium Chromium Cobalt* Copper Iron* Lead Lithium* Manganese* Molybdenum Nickel Silver Thallium Vanadium Zinc
(c)
Relative Contribution to Toxicity Potential (%)
Substance
Li-Ion Li-Poly Smart
(d)
Relative Contribution to Toxicity Potential (%)
Substance
Li-Ion Li-Poly Smart

Figure S5



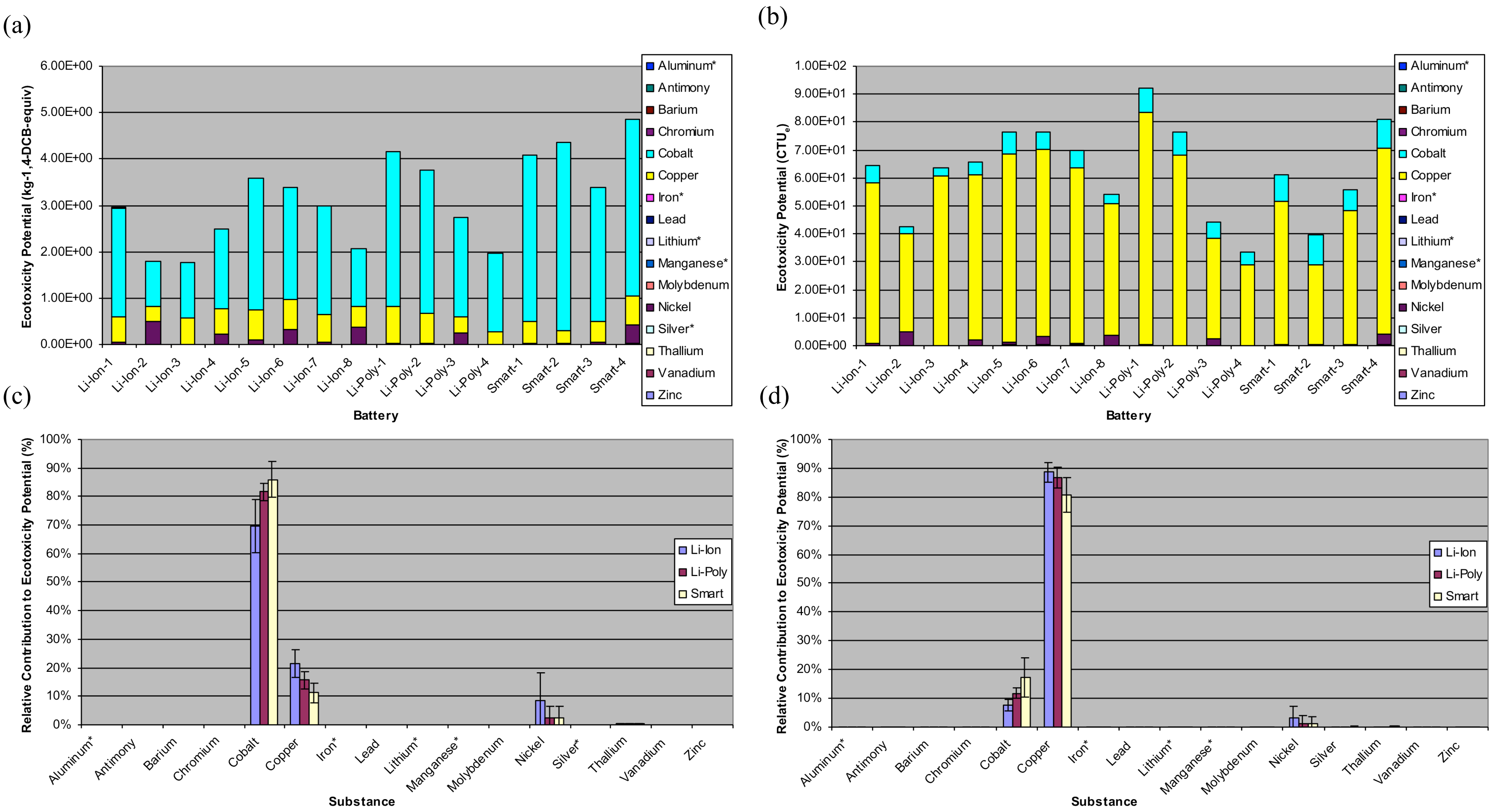
(a)
(b)
(c)
(d)
Human Toxicity Potential (kg-1,4-DCB-equiv)
Human Toxicity Potential (CTUh)
Battery
Relative Contribution to Toxicity Potential (%)
Substance
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Aluminum*
Antimony
Barium
Chromium
Cobalt
Cobalt*
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver
Silver*
Thallium
Vanadium
Zinc
Li-Ion
Li-Poly
Smart

Figure S6



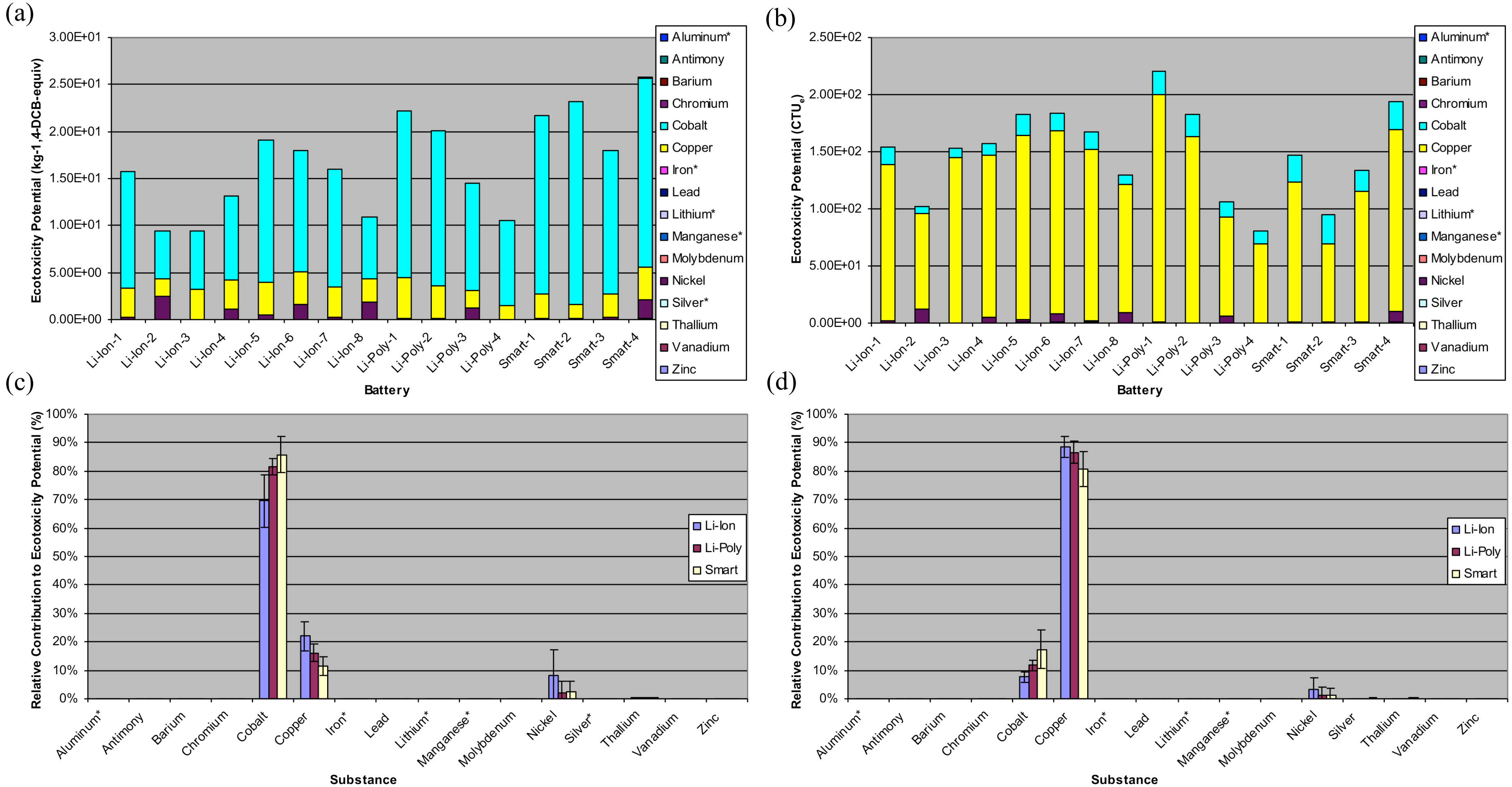
(a)
(b)
(c)
(d)
Human Toxicity Potential (kg-1,4-DCB-equiv)
Battery
Human Toxicity Potential (CTU_h)
Relative Contribution to Toxicity Potential (%)
Substance
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Aluminum*
Antimony
Barium
Chromium
Cobalt
Cobalt*
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver
Silver*
Thallium
Vanadium
Zinc
Li-Ion
Li-Poly
Smart

Figure S7



(a)
(b)
(c)
(d)
Ecotoxicity Potential (kg-1,4-DCB-equiv)
Ecotoxicity Potential (CTU_e)
Battery
Relative Contribution to Ecotoxicity Potential (%)
Substance
Aluminum*
Antimony
Barium
Chromium
Cobalt
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver*
Thallium
Vanadium
Zinc
Li-Ion
Li-Poly
Smart

Figure S8



(a)
Ecotoxicity Potential (kg-1,4-DCB-equiv)
Battery
(b)
Ecotoxicity Potential (CTU$_e$)
Battery
Aluminum*
Antimony
Barium
Chromium
Cobalt
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver*
Thallium
Vanadium
Zinc
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
(c)
Relative Contribution to Ecotoxicity Potential (%)
Substance
(d)
Relative Contribution to Ecotoxicity Potential (%)
Substance
Li-Ion
Li-Poly
Smart

Figure S9

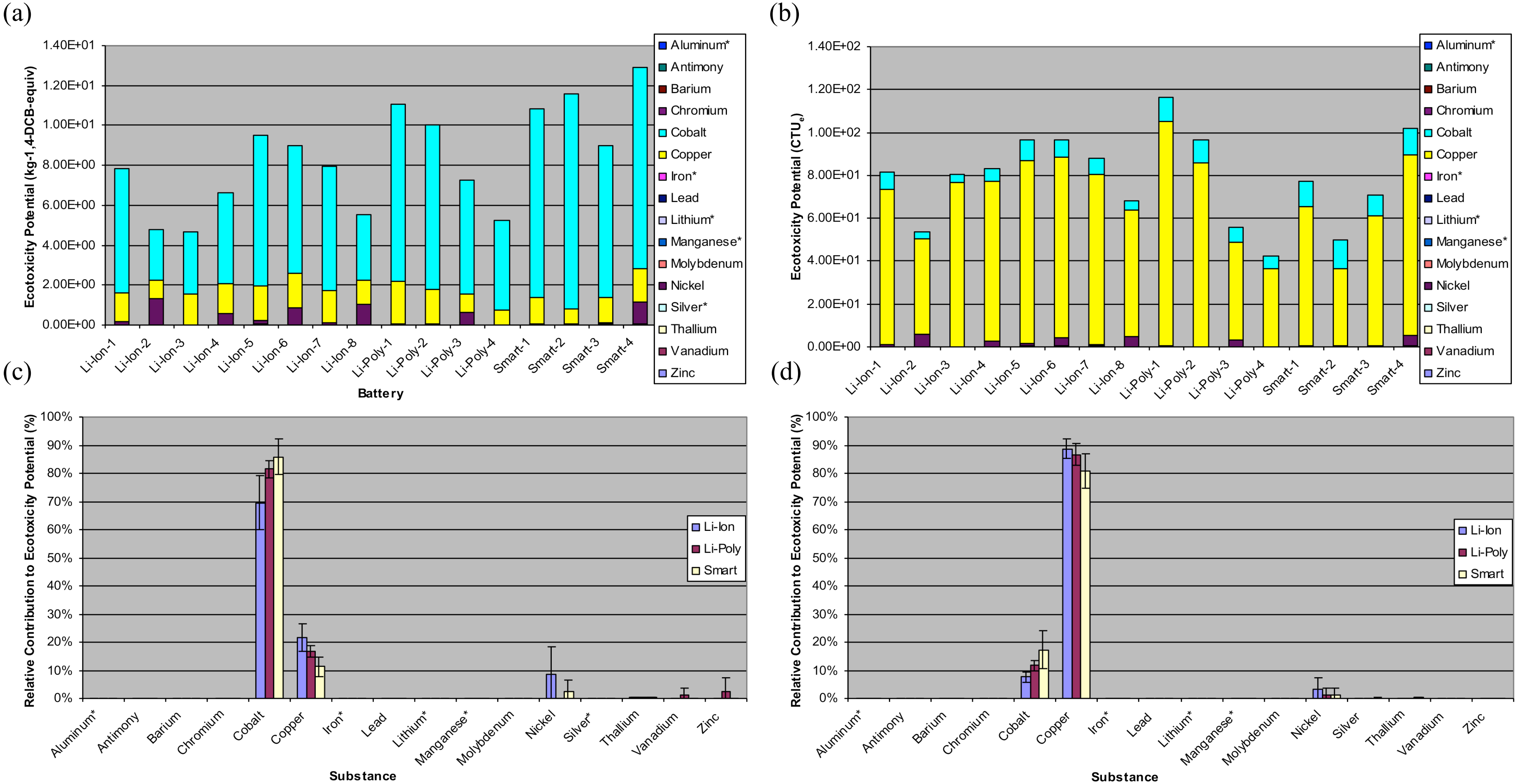

(a)
(b)
(c)
(d)
Ecotoxicity Potential (kg-1,4-DCB-equiv)
Battery
Ecotoxicity Potential (CTUe)
Aluminum*
Antimony
Barium
Chromium
Cobalt
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver*
Silver
Thallium
Vanadium
Zinc
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Relative Contribution to Ecotoxicity Potential (%)
Substance
Li-Ion
Li-Poly
Smart

Figure S10

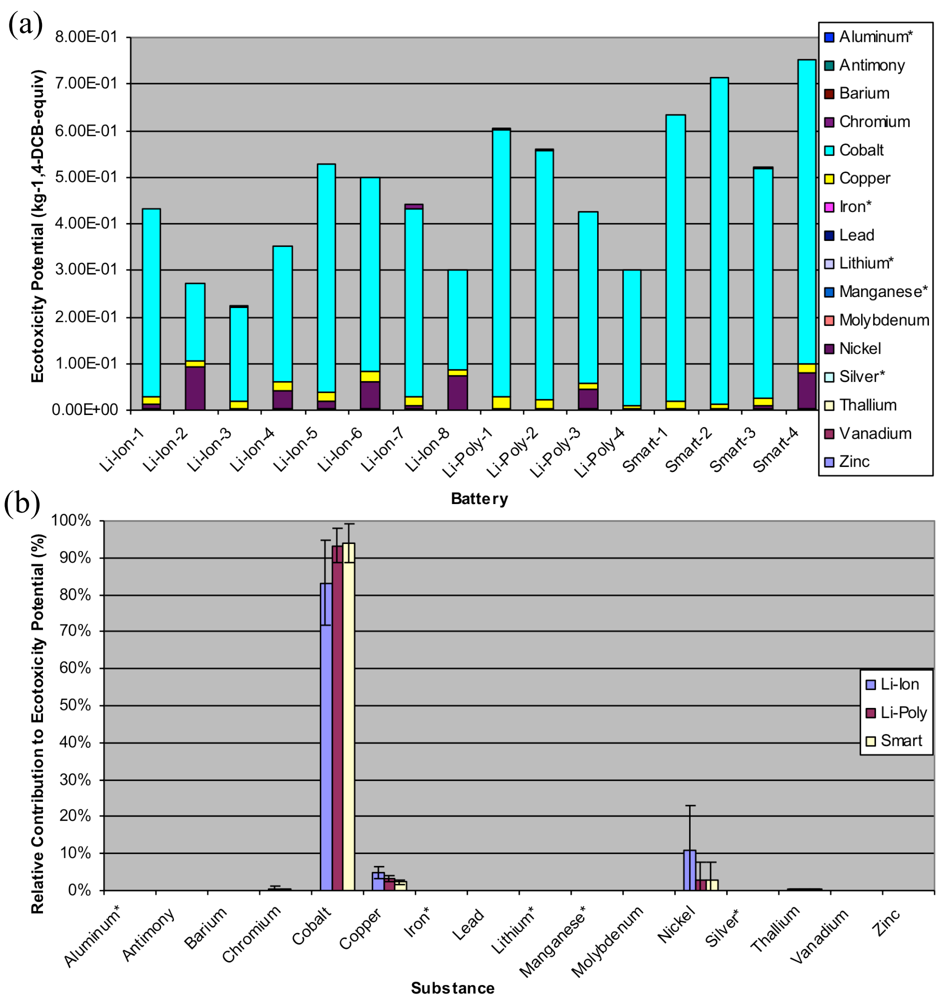
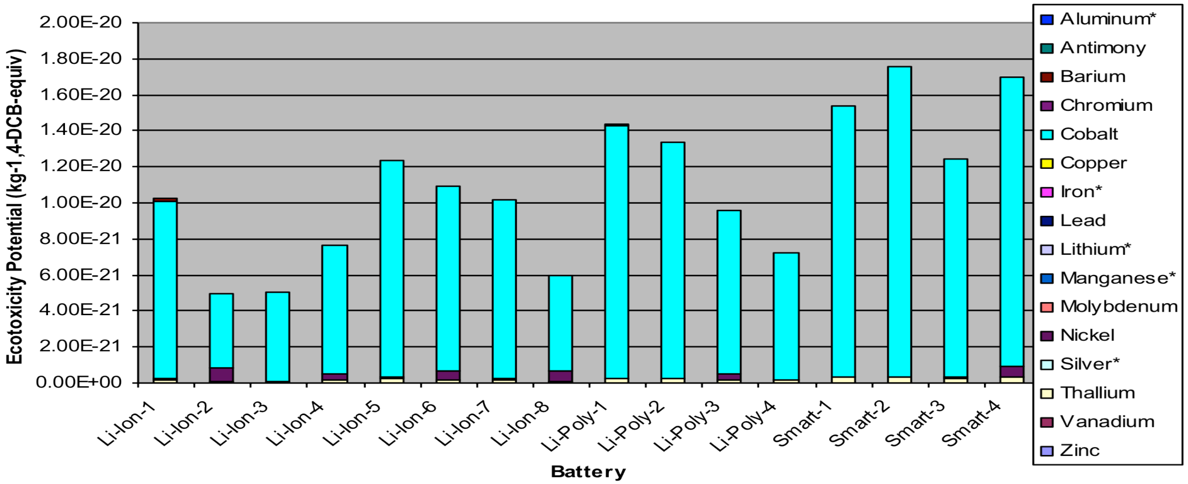

(a)
Ecotoxicity Potential (kg-1,4-DCB-equiv)
8.00E-01
7.00E-01
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Li-Ion-1
Li-Ion-2
Li-Ion-3
Li-Ion-4
Li-Ion-5
Li-Ion-6
Li-Ion-7
Li-Ion-8
Li-Poly-1
Li-Poly-2
Li-Poly-3
Li-Poly-4
Smart-1
Smart-2
Smart-3
Smart-4
Battery
Aluminum*
Antimony
Barium
Chromium
Cobalt
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver*
Thallium
Vanadium
Zinc
(b)
Relative Contribution to Ecotoxicity Potential (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Li-Ion
Li-Poly
Smart
Aluminum*
Antimony
Barium
Chromium
Cobalt
Copper
Iron*
Lead
Lithium*
Manganese*
Molybdenum
Nickel
Silver*
Thallium
Vanadium
Zinc
Substance

Figure S11

(a)



(b)

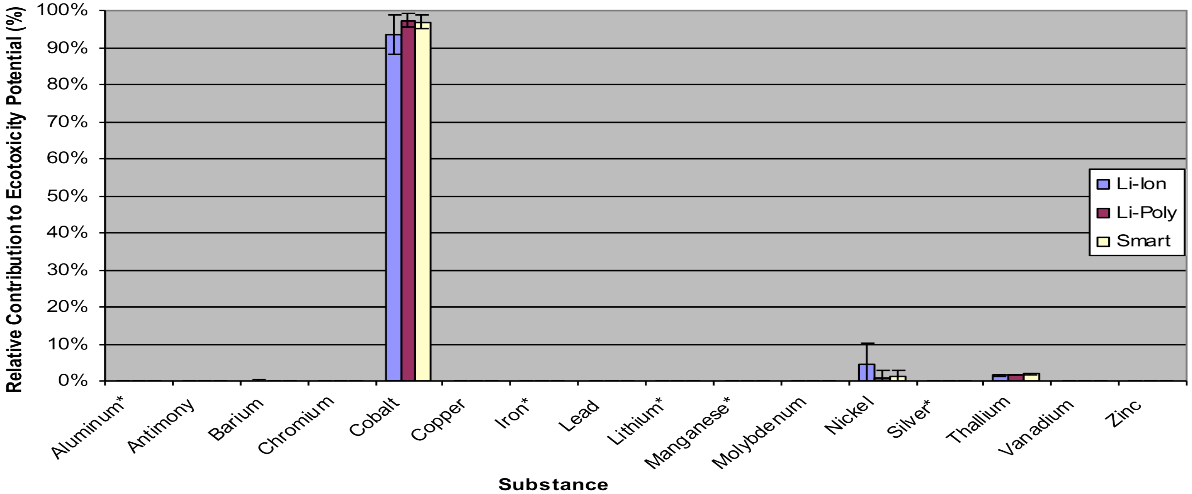
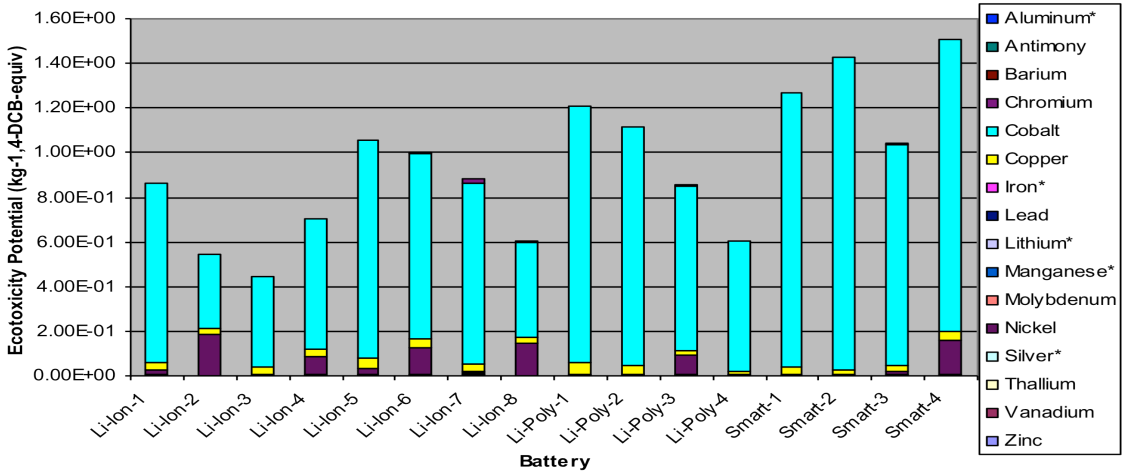


FIGURE S12

(a)



(b)